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A Comparison of Electrolytic Capacitors and Supercapacitors for Piezo-Based Energy Harvesting

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14. ABSTRACT

Energy harvesting is being investigated as an alternative to batteries for powering various Army systems. A piezoelectric system that generates energy from the oscillation of a mass on a spring (set in motion by the launch acceleration) is being developed. Typically, this energy is stored on an electrolytic capacitor for use during flight. Here we investigate a number of electrolytic capacitors and electrochemical double layer capacitors (aka, supercapacitors) for storing this energy. Supercapacitors are of interest, as they are potentially smaller, lighter, and more reliable. Here, we have investigated capacitors of different sizes as well as fast and slow supercapacitors for storing the energy. We find that capacitors of similar size store similar amounts of energy, with a system-dependant optimum size for maximum stored energy, and that the faster capacitors charge more quickly.

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Energy harvesting, supercapacitors, piezoelectric, graphene

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1. Introduction

The electronics in modern Army systems have many requirements: small size, fast power-up, and long shelf-life, to name a few. Energy harvesting systems are being investigated for replacing batteries in some of these systems. An energy harvesting system would have benefits that include improved shelf-life and storage in a non-energized state. The energy storage in these energy harvesting systems is typically done using electrolytic capacitors. Here we have investigated the performance of different aluminum electrolytic capacitors and supercapacitors for these applications. Supercapacitors have higher energy density and longer shelf-life, and should survive high accelerations better than electrolytic capacitors, which may make them desirable for energy harvesting applications.

2. Experiment

A mechanical simulator for an envisioned Army piezoelectric energy harvester was built using a custom design (see figure 1). A long cantilever mounted on torsion axes was coupled to a piezoelectric element. When the cantilever is deflected and released, it replicates the output that a mass on a spring coupled to a piezo element would produce upon experiencing an acceleration. The cantilever is equipped with a release mechanism for producing repeatable deflections. The electronic output of the piezo was rectified and stored on a capacitor using a simple full bridge rectifier (see figure 2). The output of the rectifier was measured with a digital oscilloscope with 100x probes. The charge on the capacitor under test was obtained by subtracting the voltages measured at the two rectifier outputs. All of the capacitors were also characterized with electrochemical impedance spectroscopy at 0 V using a Princeton Applied Research Versastat 3 potentiometer. The rectified output without a capacitor is an approximately 25 V peak, 20 Hz, damped waveform, as shown in figure 3.

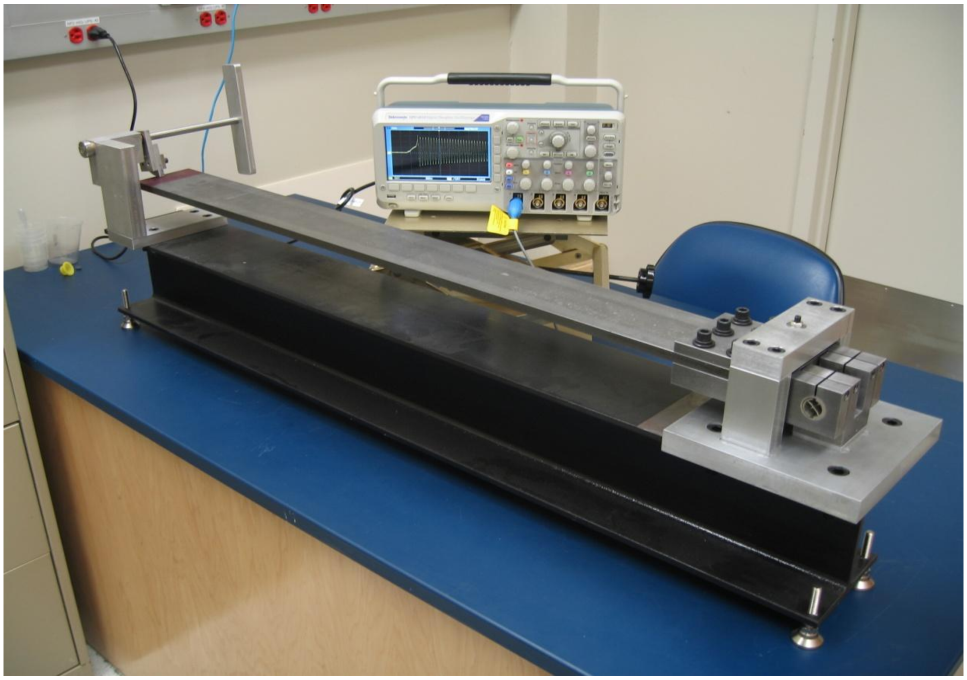

Figure 1. Cantilever coupled to a piezoelectric element (beneath the cantilever).

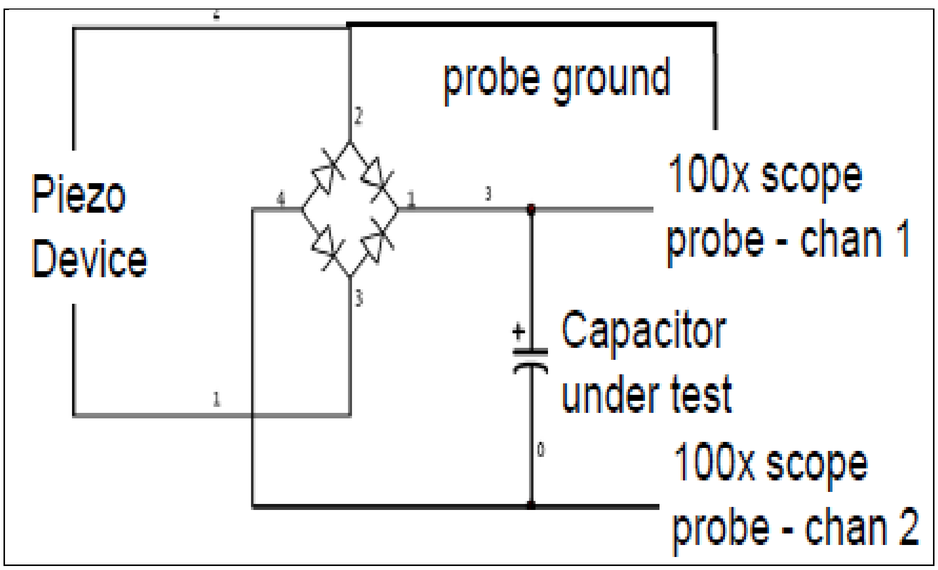

Figure 2. Capacitor charging circuit.

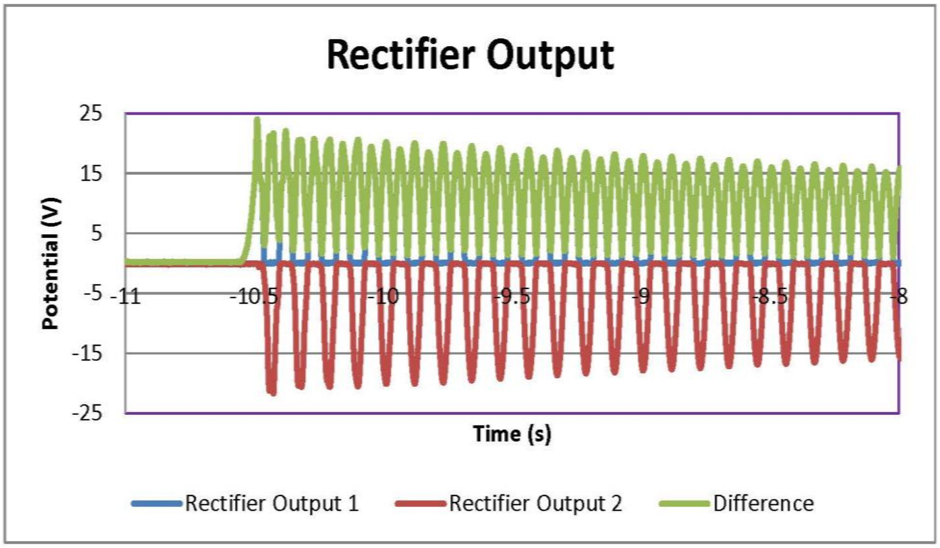

Figure 3. Rectified output from the piezo-element when there is no capacitor in the circuit.

3. Results

A variety of capacitors were tested, as shown in table 1, including both electrolytic and supercapacitors. Some of the supercapacitors were tested as six (AVX) or nine (Panasonic) supercapacitors connected in series to reduce their capacitance to match that of a readily available electrolytic capacitor. All of the capacitors are commercially available except for the JME Inc. supercapacitor. This graphene capacitor was made with plasma-enhanced chemical vapor deposition (PECVD) graphene arrays grown on nickel current collectors, and using 25% KOH electrolyte.* The capacitances reported in table 1 are measured values and differ slightly from the nominal values.

*Miller, John R.; Outlaw, R. A; Holloway B. C. Graphene Double-Layer Capacitor with AC Line-Filtering Performance. *Science* **2010**, *329*, 1637–1639.

Table 1. Measured capacitor characteristics and performance.

Capacitor	Type	Value	Equivalent Series Resistance	Freq. for 45° Phase Angle	Time to Half Charge	Energy Stored
Cornell Dubilier	Electrolytic	2.97 mF	0.0052 Ω	1.3 kHz	4.2 s	233 μJ
Panasonic	Supercap	3.06 mF	480 Ω	10 mHz	0.12 s*	233 μJ
AVX	Supercap	3.10 mF	0.88 Ω	45 Hz	3.8 s	242 μJ
Sprague	Electrolytic	212 μF	0.086 Ω	6.3 kHz	2.7 s	1.38 mJ
JME	Graphene	201 μF	0.0092 Ω	16 kHz	0.63 s	177 μJ (peak)

*Measurement artifact

Charging these capacitors with the pulse train coming out of the energy harvester simulator produced a range of performances, as can be seen in figure 4. The different capacitors stored different amounts of energy and charged at different rates.

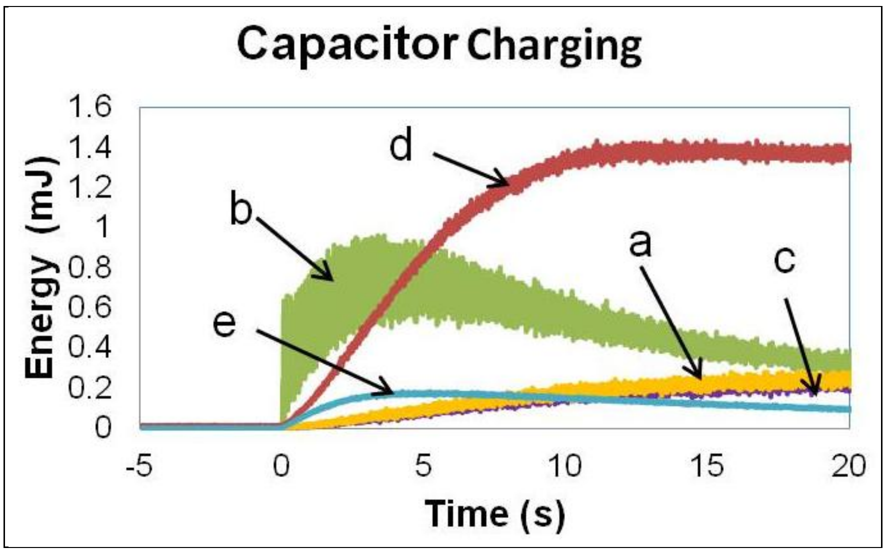

Figure 4. Capacitor charging using the rectified piezo output: (a) 2.97 mF electrolytic, (b) 3.06 mF slow supercapacitor, (c) 3.10 mF faster supercapacitor, (d) 212 μF electrolytic, and (e) 201 μF fast graphene supercapacitor.

There are a number of interesting observations to make from these results in table 1 and figure 4. First, the three ~3.1 mF capacitors capture the same amount of energy, even though the Panasonic capacitors have a much slower charge rate (as indicated by their 10 mHz frequency for reaching 45° of phase angle) than the rectifier output. This is attributed to the capacitors being charged by an RC time constant average of the rectifier output.

Secondly, the smaller electrolytic capacitor stored more energy due to the higher voltage it charged to. This is because the IN4148 diodes used in the rectifier have turn-on voltages of 0.85 V. If this voltage is added to the voltage on the charged electrolytic capacitors when calculating the stored energy, then the stored energy differences are within the run-to-run variations.

Thirdly, there are differences in the time to reach half-charge, which are more difficult to interpret. The Panasonic capacitors appear to have the fastest charging, but this is a measurement artifact. The high impedance of these series capacitors is resulting in significant IR drop across them, which is larger during the initial higher voltage output of the rectifier. This makes it appear to charge faster, but a closer look at the charging curve in figure 5 shows that much of the voltage is not charge being taken up. It is also probably true that charge redistribution limitations are reducing the effective capacitance of these devices during the initial charging, as the impedance spectroscopy shows significantly lower capacitance on time scales less than 10 s (see figure 6). This charge redistribution is why the initial charge voltage decreases.

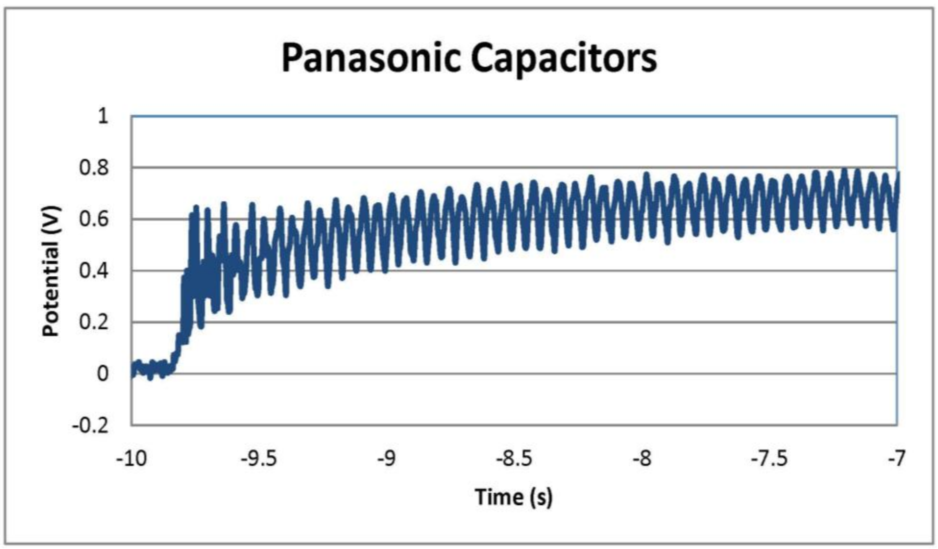

Figure 5. IR drop of the rectifier output seen across the Panasonic capacitors as they charge.

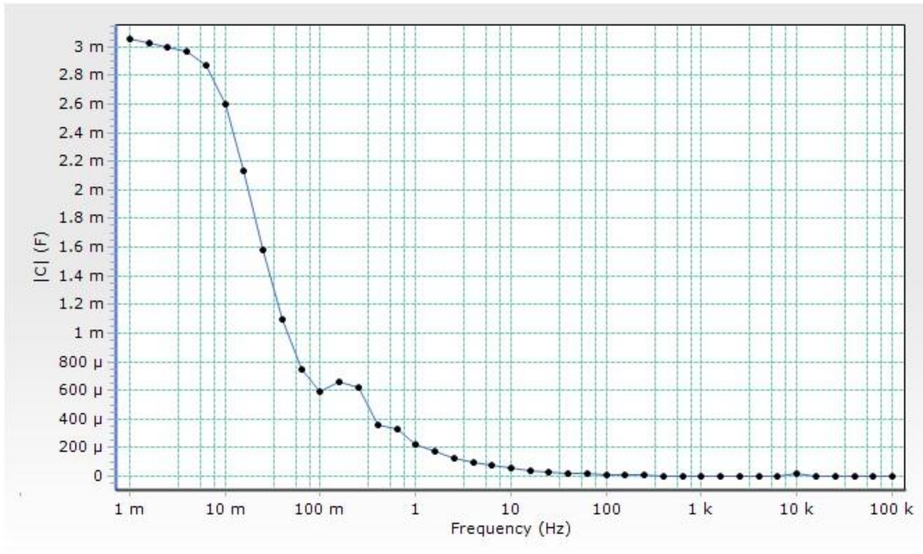

Figure 6. Impedance spectroscopy shows the Panasonic capacitors have reduced capacitance at sub-10 second time scales (>0.1 Hz frequencies).

The graphene supercapacitor prototype also showed some interesting behavior, shown in figure 7, due to its low voltage rating (as a single aqueous cell) and its lack of packaging. Most interestingly, while electrolyte breakdown does reduce the peak potential achieved, the capacitor remains overcharged (>1 V) for several seconds. This is believed to be due to kinetic limitations on the electrolyte breakdown. The temporary overcharge may represent useable energy for a short duration mission. The slower voltage decay below 1 V is likely due to a contamination or corrosion in this non-optimized prototype. It is unlikely that this voltage decay is due to charge redistribution, given its high 45° phase angle frequency.

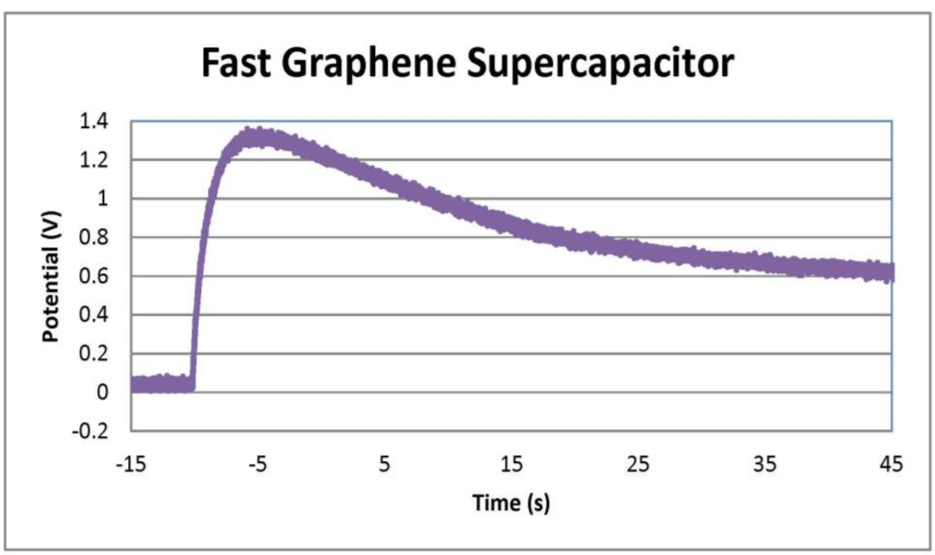

Figure 7. Charging of a fast, low-voltage, aqueous graphene supercapacitor showing initial overvoltage charging followed by self-discharge.

4. Conclusions

In this work, a number of capacitors have been investigated to determine their suitability for use in a piezoelectric energy harvesting system. It was found that similarly sized capacitors would store similar amounts of energy. Notably, while slower capacitors charged more slowly, they eventually reached a similar charged voltage. Diode turn-on voltages were found to be largely responsible for the different energies stored as a function of capacitor sizes. The rectifier diode turn-on voltages had a more significant impact on the energy stored on larger capacitors due to their lower charge voltage. The prototype graphene supercapacitor exhibited fast charging, but there were a couple of interesting self-discharge behaviors. On the positive side, potentially useful overcharging was seen for short periods enabled by electrolyte breakdown kinetics. On the negative side, once the capacitor had discharged into the electrolyte electrochemical stability window, there was still significant on-going self-discharge, probably due to a contaminating species in the prototype. With further development, the graphene supercapacitor appears to be a promising candidate for storing the energy as part of an energy harvesting system.

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